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16. Abstract

A discussion on the environmental effects on ignition and flame spread of combustible polymeric material which are used for building structures, based on recent work on ignition and flame spread of polymethylmethacrylate (PMMA; typical polymers). We also point out several problems generated from our discussion.

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I. Introduction

There have been a number of investigations concerned with mechanisms of ignition and flame spread of polymeric materials, since they relate to combustion mechanisms at the beginning and spreading time of a fire. However, most of the studies are limited under simplified conditions. Thus, in order to utilize these data to predict actual combustion mechanisms of polymeric materials which are functions of time and position, we have to impose a number of assumptions. Yet there are very few investigations on a systematic approach to predict actual phenomena. Thus, it is almost impossible to estimate how a fire starts and how flame spreads under a real fire.

In the present work, we discuss environmental effects on ignition and flame spread of combustible polymeric materials which are used for building structures, based on recent work[3-7] on ignition and flame spread of polymethylmethacrylate (PMMA; typical polymers).[1,2] We also point out several problems generated from our discussion.

2. Ignition

In Fig. 1 the mechanism of ignition and flame spread of combustible polymer materials are qualitatively shown. The heat from external heat sources propagates to the polymeric surface through radiation, convection, or conduction. / 292
Some of the heat on the polymer surface is lost by convective or radiative flows, but most is absorbed in the polymer. The absorbed heat is transmitted to the interior of the polymer and raises temperature of the polymer.

When the surface temperature attains or exceeds the thermal degradation temperature of the polymer, combustible gases, which are generated by thermal degradation, start bursting out from the polymer surface. Subsequently,

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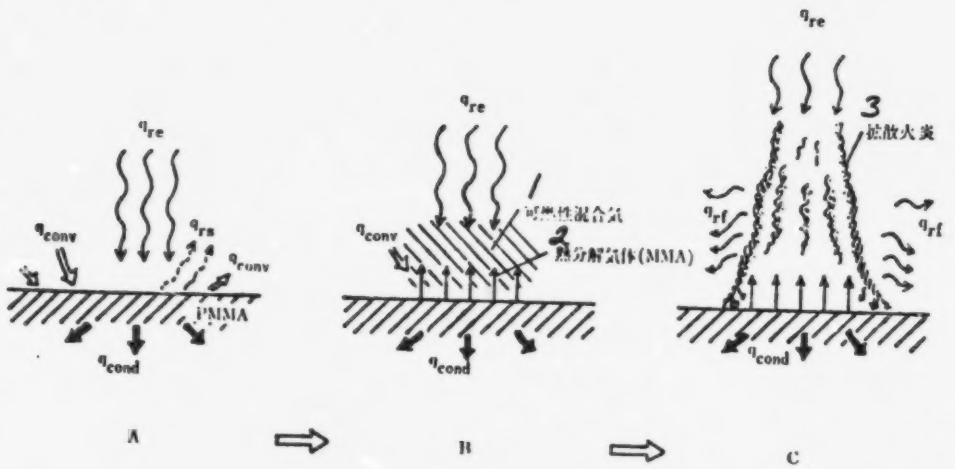

Fig. 1 Progress of a Fire Ignition of Combustible Polymeric Materials
1. combustible gas mixture. 2. thermally decomposed gas. 3. diffusing flame.

mixtures of the gases and air near the surface form a combustible gas and ignite.

In these processes, the formation of combustible gas mixtures due to an increase of the polymer surface temperature is the most dominant process for the ignition of the polymeric materials. Most discussions are thus focused on the increase of the surface temperature. Experimental data can be well interpreted if the standard temperatures are taken at the surface, i.e., the polymer ignites if the polymer surface temperature reaches the limiting temperature.[8] However, ignition occurs in the gas phase[9,10] and thus, ignition should not happen if the gas phase is not satisfied with the ignition conditions even if the polymer surface temperature becomes higher than the thermal degradation temperature.

Taking account of these facts, several theories were proposed to interpret ignition of polymeric materials from the gas phase properties.[11-13] All the theories predict that ignition starts when the temperature and concentration of the gas phase attain the limiting condition. All phenomena are considered to be one dimensional.

In Fig. 2, we show experimental data for radiative ignition of PMMA.[1] In this particular experiment, CO_2 laser light source irradiates perpendicularly horizontal over the PMMA surface. The reason to use a CO_2 laser as the heat source is that (1) heat radiation to the PMMA surface can easily controlled, (2) the properties of the heat source are well known.

In an actual fire, heat radiation intensity is strong enough to ignite PMMA. In Fig.2, radiative heat intensity ranges from the actual fire intensity to much stronger intensity.

One of the most characteristic features is that the retardation time of ignition is discontinuous, indicating that there exists a critical radiation intensity. It

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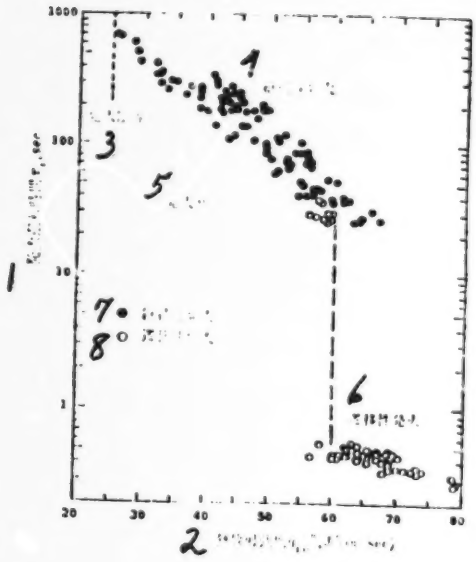

Fig. 2 Reatardation of an Ignition Time of a Horizontally Oriented PMMA Sheet Irradiated Perpendicularly.

1. retardation of an ignition time τ_i, sec. 2. thermally irradiated intensity q''_e, J/(cm^{2}sec). 3. the limiting ignition. 4. secular ignition. 5. no ignition. 6. transient ignition. 7. secular ignition,. 8. transient ignition.

is unlikely that the outburst of combustible gases is discontinuous from the polymer surface due to thermal degradation. Thus, if ignition happens right after the thermal degradation, there should be no discontinuity of the retardation time. If we assume that an ignition starts with higher radiation intensity than the critical value right after the thermal decomposition, ignition, which occurs with lower radiative intensity than the critical value, should start long after the thermal degradation. Clearly ignition itself is discontinuous, but there is no relation between discontinuities of the retardation time at the critical radiative intensity and ignition.

This leads to a conclusion that the surface temperature is not a standard temperature in order to interpret ignition of polymer materials.

Further, since temperature and concentration of gases are continuous in space and time, previous comparison between experiment and theories is incorrectly compared. Thus, agreements between data and theories are fortuitous, since most fire situations have lower heat radiative intensity than the critical value. /293

If ignition starts in the gas phase and the phenomena is not one dimensional, ignition may depend on the surface direction with respect to the gravitational force of polymer materials. In Fig. 3, we show the retardation time for PMMA surface perpendicular to the gravity, when CO_2 laser light source was irradiated horizontally to the PMMA surface. As expected, the retardation time, critical values for the heat radiative intensity, and the critical radiative intensity value for ignition are different from those for the horizontal arrangement of PMMA. Differences are schematically shown in Fig. 4. It is observed that the large differences are found in the region lower than the critical radiative intensity. In order to see such a difference further, it is important to study spacial positions where

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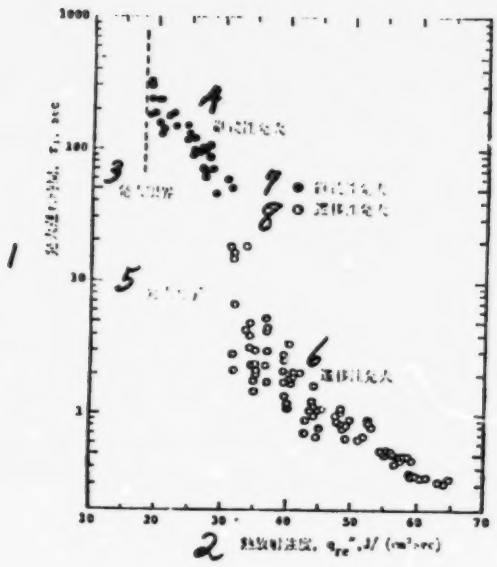

Fig. 3 Retardation of an Ignition Time of a Perpendicularly Oriented PMMA Sheet Irradiated Perpendicularly.

1. retardation of an ignition time τ_i, sec. 2. thermally irradiated intensity q^*_{re}, J/(cm^{2}sec). 3. the limiting ignition. 4. secular ignition. 5. no ignition. 6. transient ignition. 7. secular ignition,. 8. transient ignition.

ignition starts. Recent studies[1,2] investigated location of ignition for various heat radiative intensities. In Fig.5 qualitative drawings are shown. When PMMA was placed horizontally and irradiated by heat radiation over the critical value, ignition started in the upward stream of the high temperature gas away from the PMMA surface. On the other hand, when the radiation was below the critical value, it started near the PMMA surface close to the boundary of the upstream of the high temperature gas upstream.

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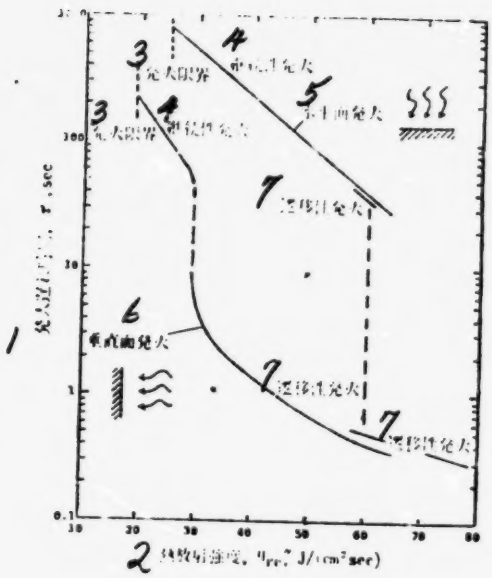

Fig. 4 Composition of Ignition Mechanisms for Horizontally and Vertically Oriented PMMA Sheets.

1. retardation of an ignition time τ_i, sec. 2. thermally irradiated intensity q''_{re}, J/(cm^{2}sec). 3. the limiting ignition. 4. secular ignition. 5. horizontal surface ignition. 6. vertical surface ignition. 7. transient ignition.

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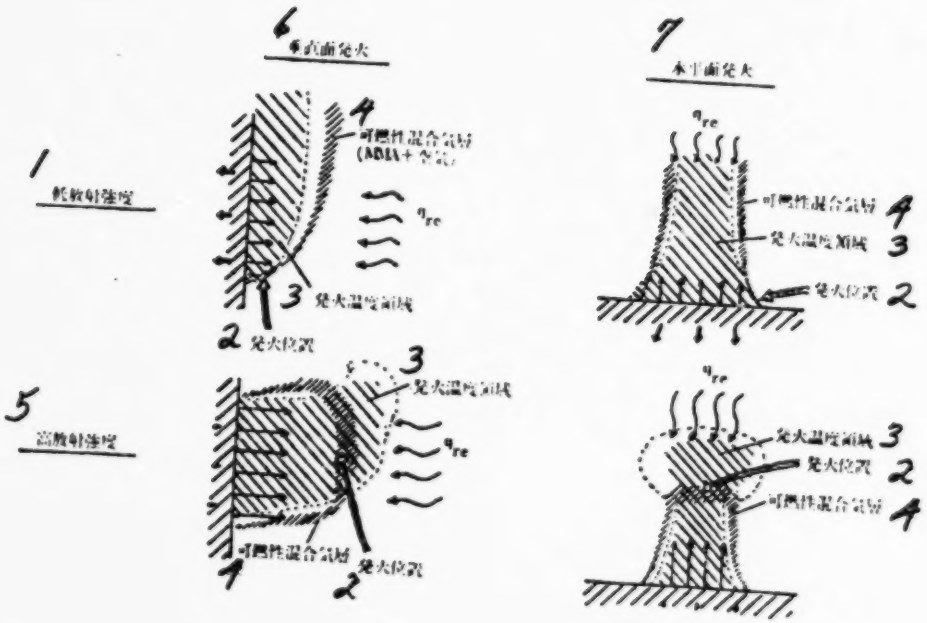

Fig. 5 Locations of Ignition.

1. low radiation intensity. 2. ignition point. 3. domains where the temperature is higher than the ignition temperature. 4. combustible gas mixture layer (MMA + air). 5. high radiation intensity. 6. vertical ignition. 7. horizontal ignition.

From temperature and fuel concentration distributions along the axis of the upward stream of high temperature gas and radial distributions of them on the PMMA surface, it was found that ignition started at the spontaneous combustible region where temperature was higher than the spontaneous ignition temperature and fuel concentration was within an active chemical reaction range.

For vertically placed PMMA, the ignition behavior is slightly different from those for horizontal surface PMMA. Ignition started at the bottom of the upward stream of high temperature gases when the heat radiative intensity was lower than the critical value. For intensities higher than the critical value, it started near the axis of the upstream of high temperature gases off the PMMA surface. The latter behavior is very similar to that of horizontally placed PMMA samples. Since heat radiative intensity is lower than the critical value for actual fires, ignition strongly depends on states of materials and surrounding gases. We speculate that the radiation time is shorter for the vertical surface than for the horizontal surface if materials are heated locally. / 294

In his recent study, Kashiwagi[16] pointed out that irradiated heat intensity should attenuate since MMA, which was generated from the heated PMMA surface, absorbed heat. Even taking into account such attenuation, our discussion in this section is still valid.

3. Flame Spread

A schematic drawing for flame spread is displayed in Fig. 6. When flame propagates over the combustible polymer surface, polymeric materials thermally degrade by heat transferred from diffusing flame by radiation and convection. The resulting combustible gases, which are generated by thermal decomposition reactions, diffuse toward the diffusing flame. There the gases react with oxygen

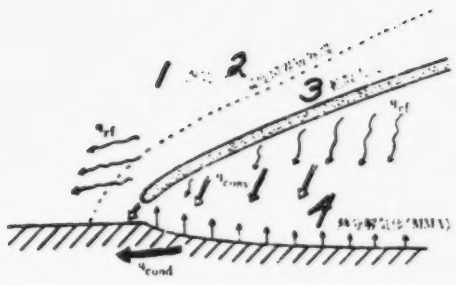

Fig. 6 Schematic Drawing for Mechanisms of Flame Spread along a Combustible Polymeric Materials.

1. air. 2. the exterior end of the temperature boundary laver. 3. diffusing flame. 4. thermally decomposed gas.

flow from surrounding air. Some parts of heat generated at the flame region propagate along the polymer surface which is under thermal reactions.

The temperature at the unburned PMMA in front of the thermal degradation domain increases by this heat transfer and reactsto a high enough temperature to start the thermal degradation reaction. Flame spreads the processes just mentioned above. The rate of flame spread increases as the heat transferred to unburned portions increases. Thus, it is very important to know the heat transfer to unburned regions in order to describe flame propagation. For vertically downward spread and horisontal spread over polymeric material's surface, rates of spread depend on the thickness of polymeric materials. In Fig. 7, the spread rate V over the PMMA sheet is plotted against the thickness δ of the sheet.[3] For the thin sheets, V is inversely proportional to δ; but for thick sheets V is independent of δ, a ratio of the energy flow into the preheated region. / 295

Figure 8 represents how heat transfer depends on δ.[3] Variations of energy

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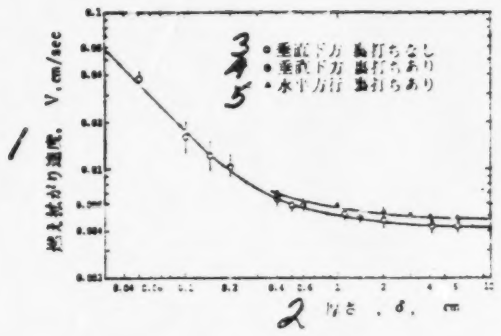

Fig. 7 Rates of Flame Spread along a PMMA Surface.
1. rate of flame spread, V, cm/sec. 2. thickness, δ, cm. 3. vertically downward, without a lining. 4. vertically downward, with a lining. 5. horizontal, with a lining.

flows for each heat transfer scheme are presented in ratio s of heat energies to the total energy q_t. A ratio of the energy flow into the preheated region, q_v, to q_+, q_v/q_t decreases as δ increases, while a ratio of the energy flown into the thermal degradation zone q_s to q_t, q_s/q_t, increases with δ. A subtraction of thermal degradation energy of PMMA from q_s yields an energy, q_x transferred through the solid phase to the unburned zone of the PMMA.

The variation of q_x/q_+ is also potted against δ in Fig. 8. The heat transfer mechanism changes significantly for a range of δ between 0. 2 - 2.0 cm. There are a number of investigations which point out that such mechanism change on various types and shapes of combustible polymers.[3,4,17-22)]

The rate of flame spread strongly depends on the slope, θ, of the polymer surface to be burned.[21,23,24)] Fig. 9 shows the rate of flame spread as a function of

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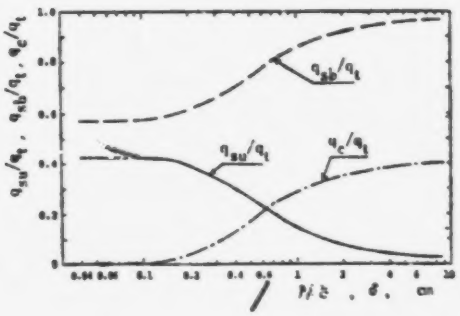

Fig. 8 Variations of Ratios of Energies, q_{su}/q_t, q_{sb}/q_t, and q_c/q_t with Thickness of PMMA Sheets. 1. thickness, δ, cm.

θ.[21,24] Similar results were known for the cylindrical surface of PMMA.[4,20] When flame propagates vertically downward, the heat transfers by conduction through the solid phase from flame to polymers ,which eventually decompose thermally if δ is large enough (Fig.10a). On the other hand, for vertically upward spread or for spread underneath the horizontal sheet, high temperature gases flow along the undecomposed zone (Fig.10b and c), and thus, most of heat flow into the solid phase from high temperature gases at the tip of the thermally decomposing zone. /296

In this case, the transfer mechanism is convective or radiative and the amount of transferred heat by these mechanisms exceeds significantly that by the conductive mechanism and is independent of δ. As mentioned above, the mechanism of flame spread strongly depends on the states of polymeric materials to be burned, especially on surrounding gas flows.

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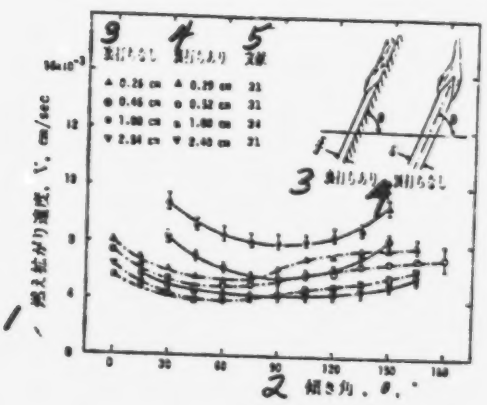

Fig. 9 Variation of Rates of Flame Spread with the Surface Orientation of a PMMA Sheet.

1. rate of flame spread, V, cm/se.. 2. slope, θ. 3. without a lining. 4. with a lining. 5. reference.

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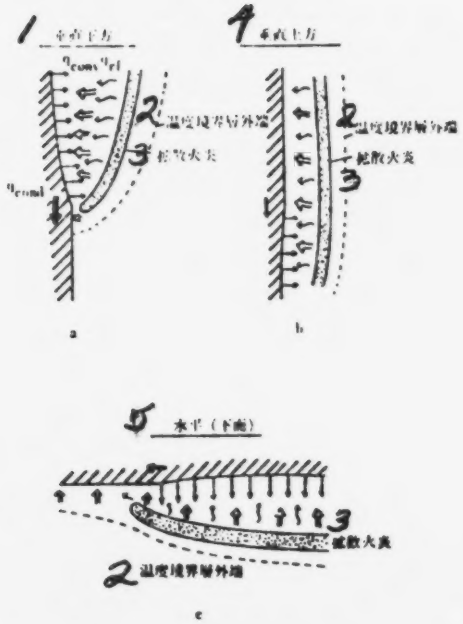

Fig. 10 Mechanisms of Flame Spread alond a Combustible Polymer Surface under Various Conditions.

1. vertically downward. 2. the exterior end of the temperature boudary layer. 3. diffusing flame. 4. vertically upward. 5. horisontal (lower surface).

4. Concluding Remarks

In the present work , we stressed that the mechanism of ignition and flame spread strongly depends on surroundings, i.e., the surface orientation of combustible polymers. One of the most influential factors of all is a flow of surrounding gases. Even if the radiative heat intensity is constant, the mechanisms of ignition and flame spread differ depending on the surface orientation (vertically or horizontally).

These facts also indicate that the combustion mechanism of non combustible materials depends on the surface orientation. Thus, it is important to make different regulations for different usages and materials with respect to floor, wall and ceiling.

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